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THE MECHANISM OF RADICAL PRODUCTION FROM THE REACTION OF N,N-DIMETHYLANILINE WITH BENZOYL PEROXIDE.

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ABSTRACT

The reaction between dimethylaniline-d_6 and benzoyl peroxide gives an inverse kinetic isotope effect of 0.93, implying that radicals primarily arise from decomposition of $Ph\text{-}CO\text{-}O\text{-}\overset{+}{N}(Me)_2Ph$ and not from electron transfer.

Many reactions that give products that can be rationalized by traditional ionic reaction mechanisms have been found in recent years to involve radical processes under some conditions. In particular, nucleophiles can react with suitable substrates either by the familiar SN2 reaction or by a radical-mediated process initiated by an electron transfer (ET) reaction.[2] In recent years, a number of groups have studied the reactions of nucleophiles with peroxides in particular, since peroxides generally give products in an irreversible step upon either one- or two-electron transfer processes.[3]

The first peroxide-nucleophile reaction that was examined is that between N,N-dimethylaniline (DMA) and benzoyl peroxide (BPO),[4] a reaction that continues to be studied since the acceleration produced by DMA is very large (10^6-fold for a 0.01 M DMA solution[5]), since it gives a 20% yield of free radicals, and since it models a number of biological processes in which an oxidative demethylation occurs at a nitrogen atom and the methyl group is primarily converted to formaldehyde.[6]

In the 1950's Horner and his group, rationalized the kinetic and product data known at that time in terms of an initial ET reaction between DMA and BPO, eq 1. In 1957, Walling[4,7,8] proposed a quite different mechanism, suggesting that the initial reaction is an SN2 process, eq 2, and that radicals arise from the subsequent homolysis of intermedical **1**, which Walling proposed undergoes homolysis faster than does BPO itself.

$$\mathrm{DMA} + \mathrm{BPO} \xrightarrow{\mathrm{SET}} \mathrm{DMA}^{+\cdot} + \mathrm{BzO}\cdot + \mathrm{BzO}^- \tag{1}$$

$$\mathrm{DMA} + \mathrm{BPO} \xrightarrow{\mathrm{SN2}} \underset{\mathbf{1}}{\mathrm{Ph}\overset{+}{\mathrm{N}}(\mathrm{Me}_2)\text{-}\mathrm{OBz}} + \mathrm{BzO}^- \tag{2}$$

Walling's sugggestion stemmed from studies[4,7] of the effects of polar solvents on the reaction rate and from the Hammett equation treatment of the reaction of ring-substituted DMA and BPO molecules; however, we have shown that these probes of effects of charge separation at the transition state do not effectively separate peroxide-nucleophile reactions into SN2 and SET types.[8]

We have previously shown[9] that the secondary β-hydrogen kinetic isotope effect (KIE) produced by substitution of deuterium at the atom adjacent to the nucleophilic center can be used to separate donor-acceptor reactions into ET and SN2 mechanistic types. In this test, inverse KIE (i.e., k_H/k_D less than unity) imply the reaction primarily occurs by an SN2 process, whereas normal KIE imply that an ET reaction has occurred. Theoretical rationalization of these isotope effects can be made on several grounds,[9] and data from a number of systems support the use of this KIE test to discriminate donor-acceptor reactions that occur primarily by SN2 and ET pathways.[9,10]

For a number of years we have attempted to apply this test to the BPO-DMA system, but we were defeated by the complex kinetic behavior of this system, including non-integral kinetic orders and irreproducible rate constants.[7] We have now discovered that reproducible rate constants and smooth first order behavior in both reactants[10] can be obtained by the use of styrene to retard induced decomposition, as discovered by Walling and O'Driscoll,[7] and by the simple but novel expedient of using BPO as the reagent that is present in excess ("flooded").

We have followed the disappearance of DMA in excess BPO in carbon tetrachloride with 0.2 M styrene to prevent induced decomposition.[10] Pseudo-unimolecular plots of ln [DMA] versus time are linear to 80% conversion, and the reaction rates are independent of the initial amine concentration. A run 0.1006 M in BPO and 0.00996 M in DMA was followed to 94% conversion, and the plot of the data as a second order reaction is linear with $k = 1.03 \pm 0.015 \times 10^{-3}\ M^{-1}\ sec^{-1}$ (correlation coefficient 0.9989). Our second order rate constants (obtained using excess BPO) agree with those of Walling, and Indictor[7a] who used excess DMA, so the reaction is clearly second order in both systems. The rate constants for the reaction of BPO with deuterated and non-deuterated DMA are given in Table I and $k_H/k_D = 0.93 \pm 0.03$. Thus, this reaction shows a 7% inverse isotope effect. For comparison, the S_N2 reaction of DMA with methyl tosylate gives an isotope effect of 0.88.[9]

The inverse isotope effect implies that the major pathway for this reaction involves the initial interaction of BPO and DMA by an SN2 reaction, eq 2, to produce intermediate **1**, and that it is homolysis of this species, as originally suggested by Walling, that is principally responsible for the accelerated production of radicals in this system. Recently, Walling[51] has argued that ET and SN2 pathways may represent a continuum and that borderline reactions may have characteristics of both. However, it is difficult kinetically to distinguish this model from the simultaneous occurrence of independent ET and SN2 reactions. To the extent that independent reactions occur, the substantial inverse KIE found here implies that the BPO/DMA system involves an initial reaction that is nearly exclusively an SN2 process.

The yield of scavengeable radicals from the DMA-BPO system is about 20%, whereas only about a 3% yield of radicals is obtained from the reaction of dimethyl sulfide with tert-butyl perbenzoate (TBP), a reaction that appears to principally involve an ET mechanism.[8,10] Thus, the initial SN2 reaction in the BPO/DMA system gives a larger yield of radicals than is obtained from the ET reaction of Me_2S/TBP, reinforcing the unreliability of using the yield of radicals as a mechanistic probe for ET in systems like these. Cage recombination of radicals, inherent radical stability, and other factors not connected with the nature of the primary reaction can determine the ultimate yield of scavengeable radicals.[10]

Table I. Kinetic Isotope Effects for the Reaction of Dimethylaniline and Dimethylaniline-d_6 with Benzoyl Peroxide at 30°C in CCl_4[a]

$[DMA]_o$	k_H, $M^{-1}s^{-1}$	$[DMA\text{-}d_6]_o$	k_D, $M^{-1}s^{-1}$
0.00990	0.990×10^{-3}	0.00975	1.078×10^{-3}
0.00982	0.949×10^{-3}	0.00991	1.025×10^{-3}
0.00999	0.981×10^{-3}	0.01030	1.055×10^{-3}
0.00970	0.966×10^{-3}	0.00971	1.030×10^{-3}
	$0.97 \pm 0.02 \times 10^{-3}$		$1.04 \pm 0.02 \times 10^{-3}$

(a) Determined by GC analysis of DMA, using *o*-dichlorobenzene as internal standard. BPO initially is 0.1 M.

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